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An Astronomical Test of CCD Photometric Precision

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Summary

Ground-based differential photometry is limited to a precision of order 10^{-3} due to atmospheric effects. A spacebased photometer should only be limited by the inherent instrument precision. Laboratory tests (Robinson, et al., 1995, Jenkins, et al., 1997) have shown that a precision of order 10^{-5} is achievable with commercially available CCDs. We have proposed to take this one step further by performing measurements at a telescope using a Wollaston prisim as a beam splitter. The resulting double image of each star is to be used to demonstrate that in actual astronomical applications the laboratory precision is achievable and can be realized for a spacebased differential photometer.

Objective

This investigation directly addresses the CCD system-level proof of concept at the one part in 10^5 level by construction and use of a ground-based Testbed to demonstrate technological readiness for the *Kepler Mission* (Borucki, et al., 1997, Koch, et al., 1996). The Testbed attempts to reproduce or come as close as practical to as many characteristics of the proposed space mission as are feasible. Specifically, the characteristics to be demonstrated include:

- Use of a real star field, along with associated background stars and diffuse galactic background;
- Use of real stellar spectra rather than a monochromatic LED;
- Use of the same ratio of point spread function to pixel size for both the *Kepler Mission* and the Testbed;
- Data processing similar to the proposed on-board data handling;
- Flux levels that are the same to show that the precision can be achieved in the same time interval;
- Pointing jitter similar to or even greater than that anticipated for the *Kepler Mission* spacecraft;
- Shutterless operation during CCD readout as in the space mission;

- A back-illuminated CCD that is thinned, delta doped, annealed and anti-reflection coated;
- Use of a two-channel readout to identify potential cross talk effects;
- Dark current at the proposed operating temperature; and
- Charge Transfer Efficiency (CTE) and full well capacity similar to that for the *Kepler Mission*.

Significance of Test

A photometric space mission has many capabilities that can contribute to a fuller understanding of the frequency and character of planets in general and uniquely to that of Earth-size planets. Our proposed mission concept has evolved (Koch, et al., 1996) to that of continuously and simultaneously monitoring 100,000 dwarf stars with no bias as to the spectral type of star to investigate. This will lead to results on characteristics of planets for a wide variety of stars, including binary and other multiple star systems. The same system can also detect giant planets around the 78,000 giant stars that will also be monitored in the same FOV. Photometry is complementary to the other existing and proposed methods. For example, a nulling interferometer cannot be used to observe planets in binary systems since it only creates a single null and is limited to only the nearest stars which are mostly M-dwarfs. And the radial velocity method is limited to stars later than mid-F-dwarfs because of the need for sufficient spectral structure in order to measure the reflex velocity. Photometry is currently the only feasible method for detecting a statistically significant sample of Earth-size planets and characterizing each individual case.

Although ground-based methods can detect giant planets and determine their properties and microlensing could provide a broad statistical sample of outer-planet frequency for galactic bulge stars, photometry is the only currently feasible method for detecting and characterizing Earth-size planets in the continuously habitable zone (CHZ) of a large sample of stars in the extended solar neighbor of the Galaxy. Three characteristics determine if a planet is potentially habitable:

1) The planet's characteristic surface temperature (assuming a blackbody), which determines if liquid water can exist. The temperature depends on the stellar luminosity and planet's distance from its star. (The albedo and emissivity are needed to be more precise);
2) The planet's mass, which determines if it can have crustal recycling and if it can retain an appropriate atmosphere or will attract a massive atmosphere making it uninhabitable; and
3) The spectral type of the star, which determines the length of time the planet's climate is continuously habitable (Kasting, et al., 1993).

Photometry can address all three of these characteristics, namely:

1) From the period and the stellar mass known from the star's spectral type, the orbital semi-major axis is calculated. From this and the stellar luminosity, the characteristic temperature can be calculated.
2) From the change in apparent brightness during a transit and the stellar size, the planet size (not just a lower limit) is calculated. By assuming a density the mass can be estimated.
3) For the brighter stars, measurement of p-mode oscillations with *Kepler* can be used as a direct measure of the stellar properties, specifically its mass to a few percent and age to about 5% (Brown and Gilliland, 1994). The spectral classification of the other stars will be used to determine their characteristics.

Results from the *Kepler Mission* will provide a statistically significant sample of extrasolar planets, determine the basic properties of the systems detected; will have the unique capability to detect and characterize Earth-size planets in the CHZ; and will provide candidate planetary systems that the *Space Interferometry Mission* can search for giant companion planets. The significance of the results from this Testbed will be to demonstrate that the photometric method has the required precision at the system level using real stars and a CCD nearly identical to that proposed for the *Kepler Mission*.

Previously Achieved Photometric Precision

We have conducted laboratory measurements to investigate the intrinsic precision of both front- (Robinson, et al., 1995) and back- illuminated Reticon 512x512 CCDs with 27μm pixels (Jenkins, et al., 1996). The back- illuminated CCD had been thinned and delta-doped (Nikzad et al. 1994), and has a full well capacity of about 4×10^5 e^- in MPP (multi-pinned phased) mode and a read noise of 12 e^- at -109°C. The CCD was operated using the SNAPSHOT data acquisition software (Dunham et al. 1985, and Dunham, 1995), providing a constant exposure time. The optical system included a 660 nm LED, diffusers, condensing lenses, several artificial star-field plates and imaging lenses. Light from the LED passed through the star-field plate, projecting artificial star fields with star images of about seven pixels in diameter full width half max (FWHM) on the CCD. The entire projection system was mounted on a micro-positioning stage, which provided reliable sub-pixel motion in both the column and row directions. No shutter was used, thereby simulating the *Kepler Mission* operation. The instrument was mounted vertically for mechanical stability and enclosed in a temperature-controlled housing. Data were accumulated as sums of 20 or 40 2.5-sec exposures on 3-sec centers resulting in approximately 2.4×10^8 e^- or 4.8×10^8 e^- in each summed image.

The system was used to conduct a number of performance tests including:

- The effects of "star trails" resulting from reading out without the use of a shutter;
- The effects of background stars up to five stellar magnitudes fainter at 10, 20 and 40 pixels from the target star; and
- The effects of sub-pixel motions on the photometric precision.

All effects were found not to degrade the precision beyond the required level of 1×10^{-5}. In each test, the summed images obtained during the experiment were processed to obtain relative light curves for each of the thirteen artificial stars. Over-clocked pixels were used to estimate the bias current, which was then subtracted from each pixel. Dark current was negligible at the operating temperature relative to the signal. The flux time series for each star was obtained by summing the counts in a 15x15 pixel window. This windowing size was chosen so that it contained at least 80% of each star's light. No non-linearity or flat-field corrections were applied to the images. Each star's flux time series was divided by the sum of the fluxes of all the other stars' fluxes to obtain a relative flux. This was normalized to its mean value. Linear least squares regressions were performed using the x and y coordinates (measured by centroiding each star) as the independent variables. Finally, the residual relative fluxes were bin-averaged by successive powers of two to assess their values for longer time scales.

As an example of one run, sub-pixel scale motions similar to those expected for the *Kepler Mission* were applied to the apparatus. The motions for this test consisted of moving the star images over a 0.08x0.05 pixel grid in nine uniform increments. After correction for motion, almost all of the scatter in the residuals can be accounted for by shot noise, yielding a residual instrument precision of better than three ppm at an integrated flux of $5.1\times10^9 e^-$. The motions were much larger than the pointing jitter anticipated for the *Kepler Mission*, so that even better precision should be achieved in practice.

In summary, back-illuminated CCDs are found to be essentially shot noise-limited differential-photometric detectors when the effects of image motion are calibrated. At the demonstrated precision of better than 3 ppm at a flux of 5.1×10^9 e^-, these CCDs are capable of detecting 80 ppm in a star's brightness change caused by transits of Earth-size planets in orbit about solar-like stars.

Description of the Testbed

The overall guideline for the Testbed is to replicate the parameters and configuration of the spacebased mission in as close a way as practical with the ground-based Testbed equipment and observing procedure using the Crossley telescope at Lick Observatory (Stone, 1979).

Based on our laboratory testing we have defined the requirements for an optimum CCD for the space mission. We have contacted a number of vendors and found that EEV can currently provide the closest match to the requirements. A comparison of the characteristics of the spacebased *Kepler Mission* configuration

Table 1 *Kepler Mission* Versus Crossley Testbed Characteristics

Parameter	*Kepler Mission*	Crossley Testbed
Aperture	0.95 m	0.90 m
System f#	1.4	5.8
Optical design	Schmidt with individual field flatteners at focal plane	Prime focus with beam splitter
Tracking	~0.1 arc sec, 1 σ	~1 arc sec
Shutter for readout	None	None
Plate scale	3.6 arcsec/pixel	0.5 arcsec/pixel
Defocus	7 pixels (25 arcsec)	14 pixels (7 arcsec)
Bandpass	0.4-1.0μ	0.4-1.0μ - sky glow filter
CCD	2048x2048 (54x54 mm)	2048x4096 (27x54mm)
Preparation	Backside thinned delta doped, AR coated	Backside thinned delta doped, AR coated
Pixel size	27μ x 27μ	13.5μ x 13.5μ
FOV	2°x2° repeated 21 times	17'x34' two overlapping beam
Vendor	EEV, SITe, MITLL or others	EEV
Well capacity	$5x10^5$ electrons/pix	$1.2x10^5$ electrons/pix
Light source	Real stars	Real stars
Readout rate	2 megapix/sec/amplifier	1 megapix/sec/amplifier

with that of the Crossley Testbed are shown in Table 1. The CCD we are using for this Testbed is an engineering grade EEV CCD42-80. The device has 3x as many bad pixels as the limit for a Grade 1 and 22 bad columns (4x the Grade 1 limit).These CCDs have a read noise of about six electrons at a one mega pixel per sec read rate and good CTE at this speed. They are backside illuminated and AR coated for a peak quantum efficiency of over 80%. Backside charging is achieved with ion-implantation followed by laser annealing. This procedure results in stable quantum efficiency and allows use of aluminum clock lines, resulting in high clock speeds. The format is 2kx4k with 13.5 micron square pixels. There are two readout amplifiers on the CCD, each servicing a 1kx4k section of the CCD. With two amplifiers, the readout time would be four seconds. However, by binning to 2x2 the read time will be one second. A modification of this basic design with 2kx1k 27 micron pixels with two amplifiers each servicing a 1kx1k section is a strong candidate for a flight detector for the proposed *Kepler Mission.* Thus the CCD42-80 is a very good choice for this proposed Testbed. We will operate the CCD at various temperatures to determine the impact of dark current on the differential photometric precision and will operate the CCD in both MPP and non-MPP mode to assess the change in both dark current and full well capacity and their respective impacts on the precision we obtain. The image in the Testbed will be defocused so that the total well capacity per star will match that for the space mission.

A controller developed by Dr. Robert Leach's group at UCSD is used to read out the CCD at one megapixel per second. This second-generation device (Leach, 1996) is the fastest highly programmable controller available. It is currently in use at more than twenty observatories. The device uses an S-bus interface. On-line documentation is available at http://mintaka.sdsu.edu/ccdlab/LabMain.html. Initially a Sparc IPX was used to run the controller. But the IPX was found to be too slow for the 1 Mpix/sec readout rate and has been replaced with a Sparc 5 running at 110 MHz. Additional application-unique software (LOIS, Lowell Observatory Instrument Software) is being developed both for this camera and other instrument development programs.

The Testbed Beam Splitter

The key component of the Testbed is a beamsplitter that will create two photometrically identical images of the real sky. The beamsplitter does not have to create flawless images. It only need maintain a brightness ratio for any pair of rays from the sky constant to 10^{-5} or better. A calcite beamsplitter known as a Wollaston prism is chosen. An optical design for this is shown in Figure 1. Calcite has the property that the indices of refraction for each polarization of the light

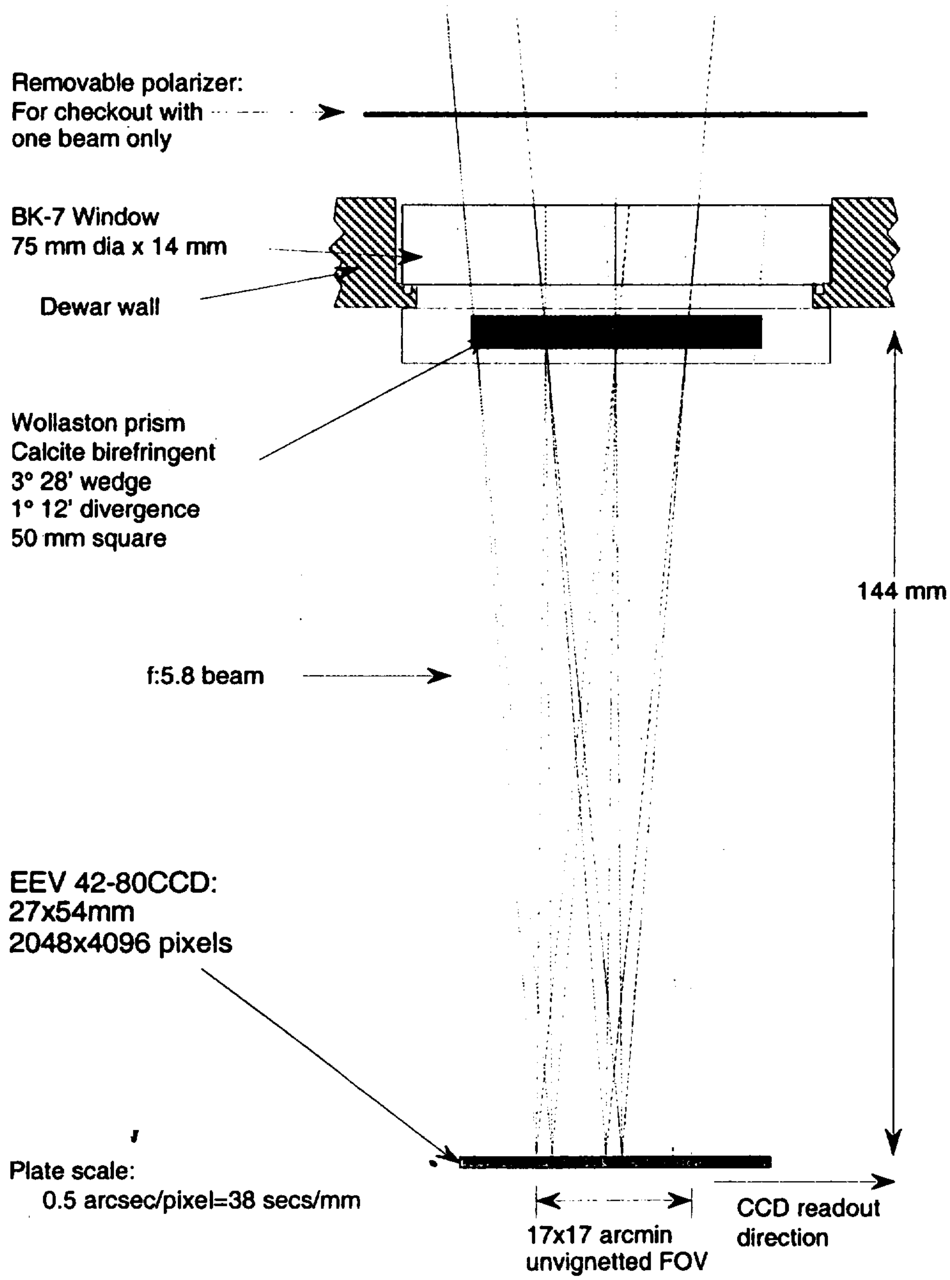

Figure 2. Testbed Beam Splitter. A Wollaston prism is used to generate two identical beams from each star to demonstrate the CCD photometric performance. Each double star image is separated by 228 pixels = 3.00 mm

differs by about 0.18 for a wide range of wavelengths. Using a small angle approximation for Snell's Law for a simple calcite prism with a prism angle of θ_p and normal incident light, the angle of the ordinary and extraordinary rays, θ_o and θ_e are given by:

$$\theta_o = \theta_p n_o, \ \ \theta_e = \theta_p n_e \ \ and \ \ \Delta\theta = \theta_p(n_o - n_e) \ (1)$$

where n_o and n_e are the ordinary and extraordinary indices of refraction of the calcite. Values of the index of refraction for calcite are listed in *The Infrared Handbook*, Table 7-21. For a prism angle of 3°28', the exit angle is 1°12'. For a distance to the CCD of 145mm the image separation is 228 pixels or 3.00mm. The CCD dimensions and read out direction are illustrated in Figure 1. It is important to note that the image is read out orthogonal to the beam splitting direction, since a shutter is not used, just as in the case for the space mission.

Several features of the optical design are the following:

1) Prior to being split, every ray passes through the same atmospheric distortion, part of the telescope and window material.

2) The beam passes through the calcite while it is still large.

3) The only place where cleanliness is critical is on the exit side of the calcite, which is kept clean by being inside of the dewar.

4) Since most of each beam passes through the same calcite, only the effects of scratches, defects or specks within 25μ of the edge of each beam can modulate the ratios (see calculation below.)

5) The Wollaston prism is parallel to the focal-plane and CCD so that both images are kept in focus.

6) Additionally, a polarizer can be inserted into the beam to select one or the other of the polarizations during instrument checkout.

The only thing that could modulate the ratio of the light in the two beams for any given star defects in the calcite crystal, scratches or dust on the exit surface in that small portion of the beam that is not common to both, as the image jitters. For a one arcsec jitter of the telescope, the beam moves by 25μm at the calcite amounting to a different beam area of 0.875 mm^2 for which a change in contamination might change the intensity ratio. Dirt and imperfections larger than 100μm are readily detectable with the unaided eye. A typical human hair is about 75μm. Both are larger than the beam displacement. Household dust that can be seen with a hand held magnifier has dimensions on the order of 5μm by 200μm. All dust larger than this can be easily detected and removed. Specifically, the effect of a 5μm by 200μm or 18μm diameter piece of dust amounts to 3×10^{-7} of the beam. A variation in surface density of thirty particles of this size or of scratches or defects in the calcite crystal would be required to have a 10^{-5} change in the brightness ratio. Hence, the imperfection and cleanliness level required, although severe, is not an unreasonable requirement. Assembly of the calcite and dewar will be done on a cleanbench.

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